Dew Effects on Passive Microwave Observations of Land Surfaces

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Water in its various forms affects passive microwave measurements of the Earth. Current and future satellite based microwave radiometer observing systems collect data during times when dew may be present. In this article, a review of studies dealing with or related to the effect of dew on microwave radiometer observations is conducted. The basic principles involved in dew formation are described, and its magnitude is quantified. Results indicate that dew is unlikely to have a significant effect on passive microwave observations at frequencies of interest for soil moisture remote sensing. Published by Elsevier Science Inc.

INTRODUCTION

Passive microwave sensors provide information on water in its various forms. By choosing the right frequencies, information on the atmospheric water vapor, precipitation, snow, or soil moisture can be extracted. One form that has not been explicitly considered is dew. Anyone who has walked across a grassy area in the early morning might think this to be a major concern based upon how wet their shoes are.

Dew formation is a temporal phenomena, and, in designing an observing system, it is possible to choose a time of day when dew is not present. However, several current passive microwave satellites such as the Special Sensor Microwave Imager (SSM/I) obtain data during times when dew is likely. Furthermore, for applications such as soil moisture measurement it is highly desirable to collect data at the time of maximum dew accumulation because this is also the time when hydrostatic equilibrium in the soil profile is most likely (Jackson, 1980).

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In this article some of the basic principles involved in dew formation are described briefly, and its magnitude is quantified. Previous remote sensing studies involving dew are reviewed. There have been very few studies conducted on dew effects, and as a result we have also included results obtained using all types of remote sensing and not just passive microwave methods. Analysis of these studies provide insight on the significance of dew on microwave measurements of land surfaces, in particular soil moisture.

CHARACTERISTICS OF DEW

The Process of Dew Formation

Dew is water that has condensed from relatively warmer air onto cooler surfaces. Three processes can contribute to dew formation: dewfall, distillation (dewrise), and guttation. Dewfall renews vapor supplies through the downward flux of vapor from the atmosphere whereas distillation is the transfer of relatively warm vapor from the soil up to the cooler surface of the leaves (Monteith, 1963). The dew from guttation arises from the plant itself. Internal water exudes from the plant when the supply of water from the roots exceeds the loss by transpiration (Hughes and Brimblecombe, 1994). The source of water is internal rather than external, and no condensation is involved. In general, dewfall and distillation are more common and significant than guttation.

The most important factors affecting dew formation are relative humidity near the surface, surface wind speeds, sky conditions, the temperature gradient between the surface and the surrounding air, and net radiation. The optimal conditions for dew formation (i.e., condensation) are as follows:

- *Relative Humidity>90% at Sunset.* High relative humidity contributes to dew formation by providing a continuous supply of water vapor for condensation and reducing the rate of evaporation (Wallin, 1963; Monteith, 1957).

- *Low Wind Speeds.* At the just the right speeds (about 1–2 m/s), the wind cools the surface of the plant. At the same time the wind mixes the air, which brings more vapor to the plant and provides a continuous vapor supply. However, extremely low wind speeds (below 0.5 m/s) do not stir up the air sufficiently and lead to a local deficiency of water vapor due to poor circulation. Moderate and high wind speeds (above 5 m/s) dry the surface of the plant and actually promote evaporation instead (Monteith, 1957).
- *Clear Skies.* Without clouds to reflect the heat radiated from the Earth's surface, the surface is able to cool rapidly (Wallin, 1963).
- *Negative Net Radiation.* As the surface of the planet cools, so do the objects near the surface. However, because dew condenses on the coolest body, the plant must cool faster than its surroundings (Monteith and Unsworth, 1991). Thus, in order for condensation to occur, there must be a difference in temperature between the air and the (plant) surface. An ideal temperature gradient between the leaf surface and the air is approximately 1–2°C (Liang and Chen, 1981).

It should be noted that different conditions favor different processes of dew formation. Dewfall's main source of vapor comes from the upper atmosphere. Thus, factors that change the conditions in the upper atmosphere will have a greater impact on the dewfall process. Low wind speeds, clear skies, and high relative humidity tend to favor dewfall. In contrast, the moisture and vapor supply for distillation comes from the ground rather than the sky. Changes in the meteorological parameters near the ground have a greater impact on dew formation by distillation. Optimal conditions of relative humidity, net radiation, and the gradient encourage dew formation by distillation.

Climatology of Dew Formation

Dew can form in any place during any season. Characterization of dew formation by climate or region is currently difficult and unreliable (Marlatt, 1971; Monteith, 1963). In fact, Monteith (1963) states that the potential condensation is virtually independent of climate. However, because there are optimal meteorological conditions for condensation, certain seasons and climates are more likely to produce dew in greater quantities and more frequently than other climates and seasons.

In almost all past studies reviewed here, maximum total dew deposition occurred during the summer. During the summer the weather is warmer, providing for a larger temperature gradient at night. Since temperatures are warmer, a liquid state rather than a solid phase condenses onto leaves. Air at warmer temperatures is also capable of carrying more moisture, which results in typically higher relative humidity values. Periods following heavy rainfalls or after monsoons show increased dew formation as well (Raman et. al., 1973) due to increased moisture content of the air. Dewfall is the most likely source of dew in humid environments. Distillation is more likely in semiarid environments.

Modeling and Prediction of Dew Events

Several dew related variables have been the focus of modeling and prediction. Some investigations have attempted to estimate the temporal accumulation of dew through rigorous energy balance modeling. Other studies have employed less sophisticated and data intensive methods to estimate the presence or absence of dew.

The energy budget of a canopy can be used to estimate dewfall,

$$\lambda E = R_n - H - G, \tag{1}$$

where

λE=latent heat flux of vaporization/condensation,
R_n=net radiation flux density,
H=sensible heat flux,
G=soil heat flux,
λ=latent heat of vaporization/condensation of water.

Estimating all of the components of Eq. (1) requires accurate and intensive micrometeorological measurements, and, therefore, this approach does not lend itself to widespread application.

Investigators such as Pedro and Gillespie (1982a), Garratt and Segal (1988), Jacobs and Nieveen (1995), and Jacobs et al. (1990, 1998) have verified the energy balance approach for specific conditions. Pedro and Gillespie (1982b) were successful at adapting the energy budget approach to use standard weather station data.

Monteith (1963) and Garratt and Segal (1988) utilized a quantity called the maximum rate of dew formation (E_p). This can be used as an index of dew formation because the actual amounts of dew have been found to correlate with this value (Jacobs et al., 1990). This value is computed using the following equation:

$$E_p = (s * R_n)/(\lambda(s+\gamma)), \tag{2}$$

where

s=the average value of the slope of the saturated vapor pressure versus the temperature in the region between the air and dewpoint temperature
γ=psychrometric constant (66 Pa K^{-1}).

Equation (2) is based upon the Penman approach as described in Monteith (1963).

Rao et al. (1998) conducted a comparison of six different methods for predicting wetness duration on maize ears. The methods ranged from three simple threshold criteria to three physical models of varying complexity and data requirements. The thresholds used were: relative humidity>90%, dewpoint depression<1.8°C, and a regression model developed by Gleason et al. (1994). This last model uses dewpoint depression, wind speed, and relative humidity. All of the models were compared against observations of the dew onset time and duration. Tests were made at the site where the meteorological station was located as well as sites at some distance from the station. The results showed that the best overall approach was based on a physically based model; however, good results were also obtained using the relative humidity threshold.

As noted above, the general availability of the data required for the application of Eq. (1) is limited. There have been few simple models developed to predict dew deposition. One model was presented by Hsu and Sakanoue (1980) that attempts to calculate the amount of dew formed with Eq. (3):

$$Y = 9.3304A + 0.2358B - 0.1348C + 0.4167D - 20.3038, \tag{3}$$

where

Y=daily dew amount (mg/cm^2/day),
A=nocturnal cooling rate of the air temperature (°C/h)
B=relative humidity (%),
C=the wind speed at 1.5 m (cm/s),
D=total net radiation (ly).

This work was performed in Taiwan, and Hsu and Sakanoue (1980) claim that the equation has a 79% accuracy rate. Other attempts to develop simple dew occurrence and duration models are described in Gleason et al. (1994) and Pedro and Gillespie (1982a,b).

Quantification of the Range of Dew Deposition

Dew, like rain, is most often measured in terms of depth or depth per unit time (night, month, or year). Typically, the measurements are expressed in millimeters. The overall consensus from the literature is that the typical range of dew deposition falls between 0.1 mm and 0.3 mm per night (0.1–0.3 kg/m^2). Baier (1966) cited other dew deposition studies performed in Germany over grass; the average rate was .024 mm/h, the range of depths was 0.06–0.5 mm, and the average depth was 0.3 mm. Monteith (1957) notes, in his general observations about grasses in southern England, that there are only 20–25 nights per year that are likely to produce 0.1 mm of dewfall. He also notes that for grasses in this particular climate that dewfall and distillation each produces an increase in canopy water content of about the same amount.

There have been other findings that claimed as much as 0.45 mm of dew per night in India (Raman et. al., 1973) and 0.47 mm on sugar beet in England (Monteith, 1963). Extreme low measurements include about 0.03 mm in Fort Morgan, Colorado (Marlatt, 1971) and 0.002 mm in southwestern Australia (Sudameyer et. al., 1994). It appears that the maximum observed value is 0.5 mm.

REMOTE SENSING AND DEW EFFECTS

The effects of dew on remote sensing observations have been investigated using visible, near-infrared, thermal infrared, and active microwave sensors. These studies take one of two approaches: providing information so that the presence of dew can be avoided when making measurements, or developing an approach to detect the occurrence of dew.

Visible, Near-Infrared, and Thermal Infrared Sensors

Pinter (1986) was concerned with the problem involved in the first approach as it related to visible, near-infrared, and thermal infrared satellite measurements. He was concerned that measurements from the morning satellite overpasses may be affected by the lingering presence of dew. It was also noted in this experiment, which utilized microlysimeters, that the observed dew was the result of distillation. For a wheat canopy in Arizona, Pinter (1986) found that dew affected the spectral bands with wavelengths less than 0.7 μm and greater than 1.15 μm. It is surprising that the 0.7–1.15 μm band was not affected because this band range is usually very responsive to the presence of water. The author attributed this phenomenon to the fact that dew forms as small spheroids instead of as a continuous layer. This leads to enhanced specular reflection. It was also found that the thermal band was not sensitive to the presence of dew. The author concluded that dew can linger into the time frame of morning satellite overpasses and affect the visible channels as well as the middle infrared.

Active Microwave Sensors

Several studies have been conducted using active microwave sensors to examine dew and related phenomena. These related phenomena include diurnal changes in the canopy and canopy interception as a result of water applied during spray irrigation or rainfall.

The first reported studies examined the diurnal variations of the canopy. This type of study is related to dew formation because at night the canopy water content can increase. It should be noted that a soil vegetation canopy can exhibit several changes as a result of the driving forces of the diurnal cycle. For the soil, during the day there will be drying due to evapotranspiration, and at night there can be surface rewetting caused by redistribution of water within the soil profile. Dewfall can also contribute to the surface rewetting. The canopy can also lose moisture during the day and regain this loss at night.

In addition, water can form on the plant as a result of dew.

The geometry of the canopy can be affected by the diurnal processes. Canopy water loss can result in wilt, and leaf orientation can change with the Sun angle. When the plant regains moisture at night the leaf will recover too. Dew on the plant leaves at night will have the opposite effect due to the added weight.

Ulaby and Batlivala (1976) examined the diurnal variation of the backscattering coefficient ($\sigma°$) measured by active microwave sensors operating between 2 GHz and 8 GHz for various crops. Based upon the fact that $\sigma°$ is determined by the target roughness and dielectric properties and that these vary as described above, it was expected that a diurnal effect would be observed. The primary experiment involved sorghum. Data were collected at different times of the day; however, they were not obtained on the same day but on different days over an 11-day period. The authors note a significant change in both soil moisture and plant height during this period. In addition, there were two fields with different surface roughness conditions that were combined in the data set. These three factors would certainly affect the measurements. Therefore, the assumption that data from different dates can be treated as a single diurnal set is incorrect. The authors identified a diurnal pattern only for the $\sigma°$ at 2.75 GHz HH polarization and look angles between 10° and 30°; however, based on the issues noted above, the validity of the conclusion is doubtful.

A better experimental design was used by Batlivala and Ulaby (1977). In this investigation data were collected over several 24-h periods for wheat, corn, soybeans, and milo. Sensor configurations included frequencies of 1.1 GHz, 4.25 GHz, and 7.25 GHz, polarizations of HH, VV, and HV, and look angles between nadir and 60°. The 24-h period measurements were made on three dates, each approximately 1 week apart during a period of active growth. Of these three dates, the only time a diurnal pattern in $\sigma°$ was observed was on the first date, and the only crop which showed any diurnal pattern in $\sigma°$ was wheat. On the first and second dates the authors note that dew was present. The fact that the canopy had not changed significantly between these two dates creates confusion over whether the dew or the canopy caused the diurnal response in $\sigma°$.

Batlivala and Ulaby (1977) found for the first set of wheat observations that the 4.25 GHz and 7.25 GHz observations were closely related to soil moisture changes in the 0–10 mm soil layer. The conclusion from this was that there was no diurnal effect related to dew or plant moisture at these frequencies. There were changes at 1.1 GHz that could not be correlated with soil moisture in the 0–10 mm soil layer. The authors suggest that the change in $\sigma°$ at this frequency is somehow related to the canopy changes. It seems more likely that the lack of correlation to soil moisture is the result of the 1.1 GHz channel responding to soil moisture in a deeper layer.

In summary, the results of Ulaby and Batlivala (1976) and Batlivala and Ulaby (1977) must be interpreted with great caution. Based on the work reported in Batlivala and Ulaby (1977), which involved nine sets of diurnal observations over a wide variety of vegetation types, with dew noted for several, for frequencies between 1.1 GHz and 7.25 GHz there is no effect of dew or diurnal plant moisture variations on $\sigma°$.

Brisco et al. (1990) also performed a series of diurnal change experiments using scatterometers (1.5 GHz, 5.17 GHz, and 12.8 GHz). Multiple polarizations and look angles were observed. Data were collected over 36-h periods on three different dates for a wheat canopy at three different stages of growth. Some level of a diurnal pattern in $\sigma°$ was observed for all sets of observations. For the one data set collected before the wheat senescence, it was concluded that changes in the plant moisture affected $\sigma°$ but it was also noted that the effects at 12.8 GHz were different than those for 1.5 GHz and 5.17 GHz.

The general results of Brisco et al. (1990) are not in complete agreement with those of Ulaby and Batlivala (1976) and Batlivala and Ulaby (1977). There were certainly differences in the experimental design and crop conditions, and these could be responsible for the differences in the results. All of the studies did see some diurnal effects on $\sigma°$ for wheat during its vegetative stage of growth. These results also point to the potential role of canopy geometry in active microwave remote sensing as being one source of the differences.

Another related type of experiment that can be used to assess the effects of dew involves making observations before and after spray irrigation or rainfall. As opposed to the diurnal type of study, the water applied by spraying will have dielectric properties similar to free water and dew. Allen and Ulaby (1984) conducted an experiment in which water was sprayed onto wheat, corn, and soybeans. Values of $\sigma°$ were obtained at 10.2 GHz HV and VV polarization for a 50° look angle. Measurements were made prior to the irrigation and then frequently after the end of irrigation. Wheat measurements were made 14 June and corn and soybeans on 1 August. In both experiments a significant amount of water was applied during the irrigation, 50 mm on 14 June and 37.5 mm on 1 August. In all of the experiments, an increase in $\sigma°$ of about 3 dB was observed between the preirrigation condition and the measurement made immediately after irrigation. For wheat there was a rapid and well-defined pattern of decrease in $\sigma°$ following the irrigation. After about 1 h the effects of the irrigation on $\sigma°$ were no longer noticeable. For soybeans, a somewhat similar effect was observed for VV polarization but not HV. With the exception of the first observation after irrigation, no effect attributable to the irrigation was observed for corn. It should be noted that when water is applied via irrigation the amount of water intercepted by the canopy is typically larger than is expected from dew. At this frequency, 10.2 GHz, the only clear effect observed was for the wheat. However, this effect could be related to the magnitude of water that was present after the irrigation. Under typical dew conditions an effect might not be detectable.

The only study that has ever been reported that dealt directly with the effects of dew on $\sigma°$ was reported by Gillespie et al. (1990). These authors attempted to evaluate what radar configuration was best suited for the detection of dew. They used 1.5 GHz, 5.17 GHz, and 12.8 GHz sensors operating at HH and VV polarizations with look angles between 10° and 60°. A wheat canopy was observed on two nights (one with dew and one without dew). The authors observed a clear sensitivity of $\sigma°$ to temporal changes only when the sensors were oriented parallel to the row direction. The 5.17 GHz HH polarization at 20° had the highest sensitivity to the presence of dew. On the night without dew, there was a similar but dampened response. The dampened response was attributed to changes in the plant moisture (the diurnal effects discussed above). Therefore, the changes detected on the night with dew contained both dew and plant moisture effects. The results of this study are quite clear; however, no explanation of why this middle frequency was the only one that responded to the dew event was offered.

From the various studies described above, it is impossible to reach a general conclusion on the effects of dew on $\sigma°$. The variety of results for different experimental designs, crops, growth stages, and sensor configurations suggests that besides a possible effect related to a change in dielectric properties that an important impact of dew on the response may be by its impact on canopy geometry. Canopy geometry effects on $\sigma°$ are related to the original structure and dimensions of the canopy constituents as related to the sensor configuration.

Passive Microwave Sensors

It is well known in studies of the atmosphere and vegetation that water in these layers modifies the signal from the soil background. For high frequencies (>10 GHz) the presence of water vapor in the atmosphere attenuates the emission from the Earth's surface. The equivalent depth of water present in the atmosphere is on the order of 10–60 mm (10–60 kg/m^2) and is spread over several kilometers. Below 10 GHz the effect of atmospheric water on measured surface emission is very small.

The presence of vegetation also attenuates the emission from the soil. For soil moisture studies, the vegetation effects can usually be accounted for at frequencies below 5 GHz. At higher frequencies there is very little soil moisture information in the signal in the presence of vegetation. Vegetation water contents can range from 0.5 kg/m^2 for grass to 6 kg/m^2 in a mature corn canopy. Sometimes the vegetation is treated as a cloud layer, and the water present is considered to be distributed uniformly over the height of the vegetation (Ulaby et al., 1986). There are other modeling approaches that attempt to take into consideration the distribution of the individual plant elements and the water density within each (Ulaby et al., 1986). At lower frequencies, the structural aspects of the vegetation are less significant (Jackson and Schmugge, 1991).

Although the depth of soil that contributes to a microwave measurement varies with the dielectric profile of the soil, it is generally accepted that the depth can be approximated as about 0.25 of the wavelength. For example, at 1.4 GHz the contributing depth is approximately 50 mm. Typical soil moisture values are between zero and field capacity. Field capacity refers to the moisture content below which gravity does not drain water. A representative value of field capacity is 30%. The equivalent water depth in the contributing soil depth at a field capacity of 30% is 15 mm (15 kg/m^2).

There are very few references that mention the effects of dew on microwave emission in the literature. Heymsfield and Fulton (1992) studied SSM/I data in Oklahoma and found no evidence of dew effects on the SSM/I brightness temperatures. They based this on predawn F8 SSM/I satellite data and dew point temperature measurements.

Jones and Vonder Harr (1997) examined diurnal patterns in SSM/I data for 70 days centered on August and September. They analyzed data for the entire central United States. When they compared data collected by the F8 satellite at a nominal local overpass time of 6:00 a.m. (when dew would be most likely) with F10 satellite data collected at 10:00 a.m. (when there should be no dew), they were not able to detect any apparent differences in the emissivities. The seasonal and regional conditions these investigators looked at were favorable to dew formation; therefore, dew events should have occurred. In addition, the emissivity retrieval approach of Jones and Vonder Harr included cloud screening so that only clear sky conditions were used in the analysis. In a previous section it was noted that clear sky conditions are conducive to dew formation; therefore, the set of data these authors used was likely biased toward dew events.

Wigneron et al. (1996) examined the effects of water interception in a controlled condition ground based experiment. They collected 1.4 GHz and 5 GHz passive microwave data over a wheat canopy before, during, and after an irrigation. An effect was observed at 5 GHz but not at 1.4 GHz. The effect observed was the water interception by the wheat canopy. The magnitudes of the interception were on the order of 1–2 mm (1–2 kg/m^2) from a total irrigation of about 15 mm.

Starting with a very dry soil condition, it was observed that during irrigation the brightness temperature (T_B) did not change at a frequency of 5 GHz. Shortly after the end of irrigation, the T_B began to decrease for the next 5 h. These results clearly show that water intercepted by the canopy masks the change in soil moisture due to irrigation. This effect was not observed at 1.4 GHz, and is likely to occur at frequencies higher than 5 GHz. These results may be interpreted to mean that dew, which is very similar in distribution and state to intercepted water, can mask the underlying soil at high frequencies. However, an important difference between the dew and intercepted water is the total depth. Dew will be an order of magnitude smaller in depth than the intercepted water amounts reported by Wigneron et al. (1996).

In retrospect, there were two aspects of the experiment described by Wigneron et al. (1996) that would be interesting to expand. First, if enough information was available to estimate the evapotranspiration of the wheat, it might have been possible to determine the attenuation effect of the canopy as a function of the amount of intercepted water remaining following the cessation of irrigation. Second, the original experiment started with a very dry soil. Under this condition the initial T_B is quite high, which makes it difficult to observe a distinct canopy effect at 5 GHz. If a second irrigation had been initiated once T_B had leveled off at a low value following the first irrigation, it might have been possible to track the increase in T_B as more water was intercepted by the canopy.

FIELD EXPERIMENT RESULTS AND DISCUSSION

To illustrate the process of dew formation on soil and canopy moisture, a field experiment was designed to evaluate the temporal nature and magnitude of dew deposition. The experiment does not distinguish between the various sources of dew, and assumes all condensation on the samples was a result of dew. The quantification was performed gravimetrically, and assumed that the changes in mass are reflective of the amount of dew formed. The experiment was conducted in Beltsville, Maryland on the North Farm. A basic weather station was located nearby.

The experiment lasted from noon on 22 August 1996 to noon 23 August 1996. There was no rain the preceding evening, nor did it rain the evening of the experiment. At sunset, the skies were clear except for one or two clouds in the distance.

Two types of samples were used: bare soil and sod. For the bare soil, the soil samples were prepared the day before the experiment. The soil was oven-dried for 24 h and sealed in plastic bags for later use. Prior to moving it to the field site, the soil was distributed into five aluminum pans of known dimensions and mass. Soil depth and mass measurements were taken at noon. The depths of the soil samples ranged between 15 mm and 30 mm. Gravimetric measurements were also recorded at 16:00, 18:00, 19:55 (sunset), 06:20 (sunrise), 07:00, 07:30, 08:00, 08:30, 09:00, 09:30, 10:00, and at 12:00. The sod experiment followed similar procedures. One piece of sod (about 0.5 sq m) was obtained the day of the experiment to ensure freshness. It was then divided up into five rectangular pieces, and each was placed into a pan of known mass. Each piece of sod was roughly 190 mm per side and between 25 mm and 38 mm thick. Initial measurements of mass were taken at 15:30. Subsequent gravimetric measurements were recorded at 16:00, 18:00, 19:55 (sunset), 06:20 (sunrise), 07:00, 07:30, 08:30, 09:00, 09:30, 10:00, and 12:00.

At 16:00, one of the soil samples and one of the sod samples were covered to prevent dew accumulation in the sample. They were both uncovered at 08:00 the following morning. This attempt at establishing a control failed and the data were ignored because of possible dew deposition. After 12:00 on 23 August 1996 the soil and sod samples were oven dried and then weighed.

Bare Soil

The gravimetric soil data for each sample are plotted against time in Figure 1. From the time of initial exposure (22 August 1996 at noon) until sunset (22 August 1996 at about 19:55), the masses for the soil samples increased. Since dew formation would be extremely unlikely during this time of day, this increase is probably due to the very dry soil absorbing moisture from the air. One of the samples had a decrease in mass during this time period. This may be a result of the soil sample preparation. After the soil samples were oven-dried, they were allowed to sit indoors for several hours in sealed plastic bags. Despite the precautions taken, the samples may still have absorbed moisture from the air while in preparation. Evaporation of this moisture when the sample was placed in the field would cause a decrease in mass.

From sunset to about sunrise (23 August 1996 at about 06:20), all of the soil samples underwent a net increase in mass. Since the samples were in pans, the increase in mass was the result of dewfall. The majority of the samples had their greatest mass measurements near sunrise, and all samples obtained maximum mass measurements within 40 min of sunrise. Mass increases ranged from 2 g to 7 g. Although no measurements were made from sunset to sunrise, Wallin (1963) suggested that a linear relationship might be used to approximate the increase during hours of dew formation.

From sunrise until noon, the masses for the soil samples decreased to near their initial masses. Several unusual readings occurred between sunrise and noon. Possible explanations for large drops in the mass mea-

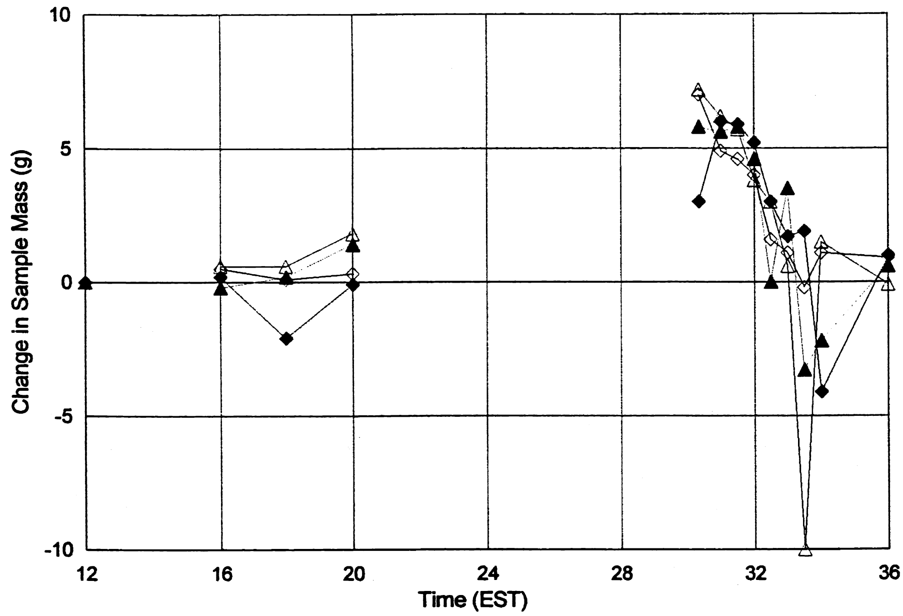

Figure 1. Results of bare soil experiment at Beltsville showing the change in sample mass (four replications) as a function of time of day.

surements of the soil samples include reading fluctuations due to the wind, and inaccurate measurements due to slightly uneven ground. Gravimetric and volumetric soil moisture, bulk density, and mass-to-surface-area ratio were calculated for each soil sample. The initial volumetric soil moisture varied between 1.39% and 1.86%, with an average of 1.59%. When applied to the entire depth of the sample, the total change in mass would correspond to a soil moisture increase of 0.6%, a very small amount. Of course, the dew added moisture is not distributed over the entire depth.

Sod

In Figure 2 the change in mass of each sod sample is plotted against time. In this graph, changes in mass are referenced to the 22 August 1996 20:00 measurement when the sod began to gain mass. Figure 2 shows a rapid decrease in mass from the time of initial exposure (22 August 1996 at 15:30) until sunset. As sunset approached, however, the rate of drying decreased. This decrease in the rate of drying is probably due to the decrease in solar radiation and the diminishing moisture content of the sod. Sod samples lost between 15 g and 40 g. One reason for the large difference in mass loss between the soil and sod samples can be attributed to the (relatively) large initial moisture content of the sod.

From sunset to sunrise, all of the sod samples experienced a net increase in mass. The sod samples reached a maximum gain between 4 g and 8 g, slightly greater than the mass gains observed in the bare soil samples.

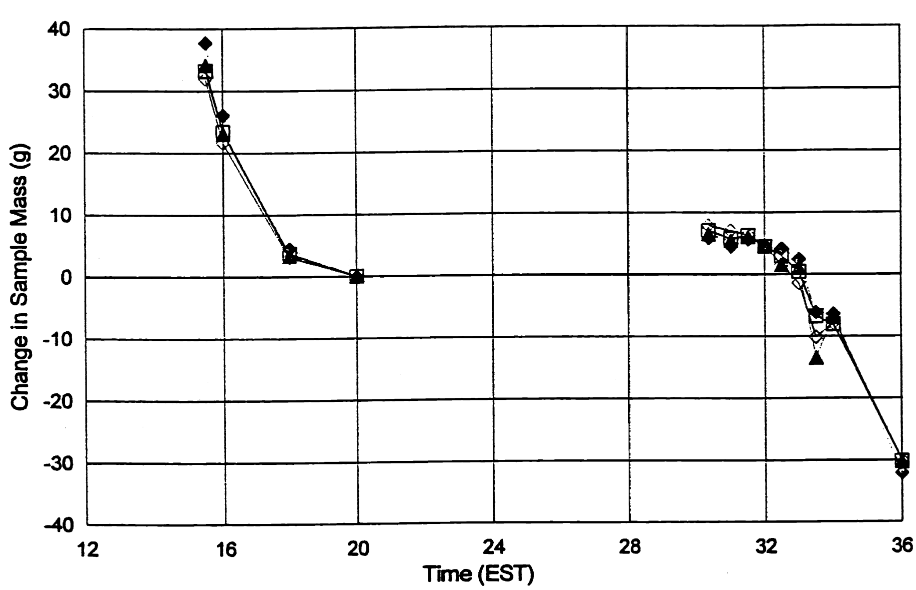

Figure 2. Results of sod experiment at Beltsville showing the change in sample mass (four replications) as a function of time of day.

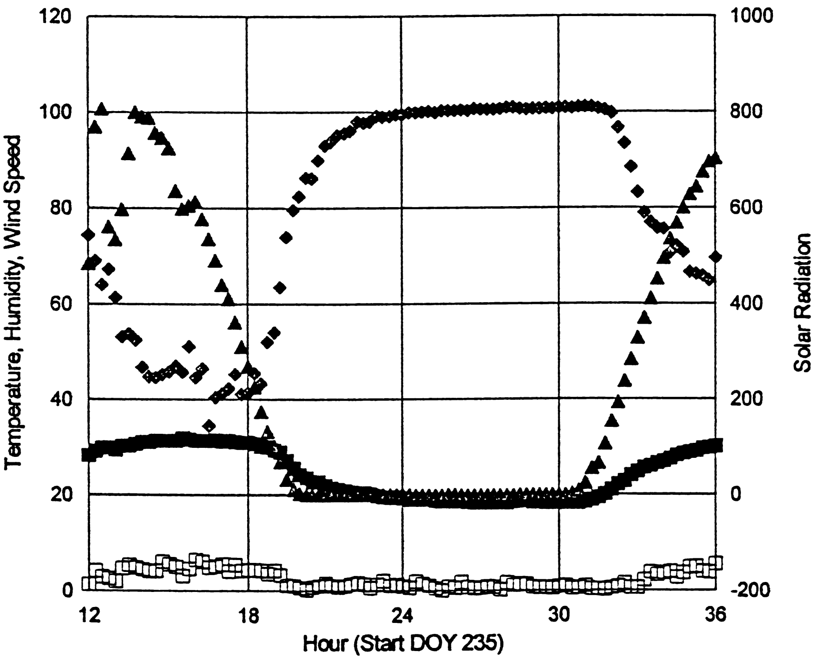

Figure 3. Meteorological observations for the Beltsville site: (■) air temperature (°C); (◆) relative humidity (%); (▲) solar radiation (w/m^2; (□) wind speed (mph).

Again, all of the sod samples obtained maximum mass gain at sunrise.

Afterwards, the mass of each sod sample decreased by over 100 g. The rate of decreasing mass increased as the time approached noon. The calculated average for the dew mass-to-surface-area ratio was 0.19 kg/m^2, ranging between 0.15 kg/m and 0.22 kg/m^2.

The available meteorological station data are plotted in Figure 3. The relative humidity was above 90% for a total of 11.5 h, between 21:00 and 08:30. Fluctuation between these hours was small. Net radiation (approximated as solar radiation less than or equal to zero) was negative for a shorter period of time—from 20:30 to 06:00. The magnitude of outgoing radiation never passed beyond 0.4 w/m^2. Lastly, the winds that night were relatively calm, with short spurts of activity of 1 to 2 m/s near 22:00, 01:00, and 04:00. Given this set of data, there were only 3.5 h in which dew possibly could have formed. Using Wallin's approximation (Wallin, 1963), the station data yields 3.48 hours of dew formation. The model given by Hsu and Sakanoue (1980) yields 0.167 mm of dew per night for the recorded meteorological data, which is a fair agreement with previous studies.

SUMMARY

Passive microwave sensors provide information on water in its various forms. One form that has not been fully explored is dew. Several current passive microwave satellites obtain data during times when dew may be present. Some applications such as soil moisture measurement are optimized by obtaining measurements at the time of maximum dew accumulation because this also is the time of hydrostatic equilibrium in the soil profile.

As illustrated with references, dew can occur almost anywhere. Many factors contribute to dew formation, however, the critical piece of information for microwave radiometry is that the average amount is on the order of 0.2 mm of water in a given dew event. A maximum value would be on the order of 0.5 mm. These values are extremely small when compared to the water depths found in the atmosphere, canopy, and soil. Therefore, it is not surprising that dew is not considered to be a significant factor for passive microwave observations of land.

Previous related research focused primarily on the use of active microwave measurements. Of the several studies reported, which observed diurnal variations and/or dew, the results are inconclusive and often in conflict with other studies. Part of the problem with these investigations may be associated with experimental design and controls.

Based upon the published results and the well-documented levels of dew deposition, dew should not have any effect on L band (1.4 GHz) observations. At extreme levels it may effect C band (5 GHz). Therefore, microwave observations at these frequencies during maximum dew deposition are usable for soil moisture remote sensing. Higher frequency measurements should be interpreted carefully.

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